Thermodynamic optimisation of supercritical CO_2 Brayton power cycles coupled to Direct Steam Generation Line-Focusing solar fields

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ABSTRACT: In this paper a new generation line-focusing solar plants coupled to a s-CO2 Brayton power cycles are studied. These innovative CSP will increase the plant energy efficiency, and subsequently optimizing the SF effective aperture area and SF investment cost for a fixed power output. Two SF configurations were assessed: the Configuration 1 with a condenser between the SF and the Balance Of Plant (BOP), for Turbine Inlet Temperatures (TIT) up to 400°C, and the Configuration 2, for higher TIT up to 550°C, with steam compressors in SF for pressure drop compensation. Both alternatives are interchangeable in the same CSP, and boosting with a backing boiler to warranty the plant performance. In relation to the BOP three configurations were studied the Recompression cycle (RC), the Partial Cooling with Recompression cycle (PCRC), and the Recompression with Main Compression Intercooling cycle (RCMCI), all these solutions without ReHeating. The methodology considered the thesis developed by Dyreby [1] as starting point, fixing the Brayton cycles recuperator conductance (UA), and optimizing the power cycles performance by means of the SUBPLEX [2] algorithm. The cycles optimal operating parameters were calculated with a "Windows" desktop application, called Supercritical_CSP (SCSP), calling the supercritical fluids properties database REFPROP, developed in C#, calling Fortran compiled dynamic linked libraries. The results obtained from the Brayton cycles optimizations were exported to Thermoflow [3] for SF simulation and design. The mathematical algorithms UOBYQA [4] and NEWOUA [5] were also integrated in the SCSP tool, for validating the SUBPLEX results. The HTF studied was Direct Steam Generation (DSG) in the SF, and the solar collectors simulated were PTC and LF. The plant net power output, the net efficiency, the SF effective aperture, were computed at Design-Point. As main conclusion obtained it is confirmed minimum Pinch Point in heat exchangers is the main constrain, reaching a threshold in the net plant efficiency, when increasing the Low Temperatura Recuperator (LTR) and High Temperature Recuperator (HT) conductances UA. The shell-tubes heat exchanger types are the most suitable solution to couple the Balance Of Plant (BOP) and the SF. The target of future works will be aligned with the analysis of innovative linear solar collectors, as the Norwich Technologies company solution, for getting higher TIT as provided by Central Tower CSP. The s-CO_2 BOP equipments detail design and detailed cost estimation are pending items under industrial development. Finally, the annual plant performance calculation, considering the variable ambient temperature and Direct Normal Irradiance (DNI), and the TES integration, are future researching works for calculating the Levelized Cost Of Energy (LCOE) in this new generation line-focusing solar power plants.

Key words: Direct Steam Generation, supercritical, Carbon Dioxide, Brayton cycles

INTRODUCTION

Direct Steam Generation (DSG) in Line-Focusing solar collectors is a technology maturing and first pilot industrial installations were already in operation. Puerto Errado 1 and 2 (PE-1, PE-2) [6], in Murcia, Spain, are the most important projects with DSG in Linear Fresnel (LF) solar collectors, and the TSE-1 project [7] in Thailand is the important Concentrated Solar Power Plant (CSP) with DSG in Parabolic Trough solar Collectors (PTC). The DSG main advantages are: no environmental impact, low material corrosion in receivers and SF headers, requiring a low alloy low cost steel, no heat tracing required for avoiding HTF solidification, high Turbine Inlet Temperatures (TIT) around 550ºC, improving the plant efficiency. Nowadays most of the Line-focusing Concentrated Solar Plants (CSP) in operation, with Parabolic Troughs solar Collectors (PTC) or Linear Fresnel (LF), integrates a Solar Field (SF) with Thermal Oil as Heat Transfer Fluid (HTF) coupled to a Rankine power cycles.

Supercritical s-CO_2 Brayton cycles are being developed as the alternative to the Rankine cycles for reducing the BOP equipments dimensions, mainly the turbines, and hence optimizing the power plant civil works. The supercritical working fluid in BOP reduces the compressors works and increase the plant energy efficiency. In Brayton cycles the only phase is the supercritical state without any phases changes, reducing the design complexity. The s-CO2 power cycles constitute the key stone for the new generation CSP as stated in reference [8]. This paper is the continuation of the paper [9], now integrating the algorithms (SUBPLEX, UOBYQA and NEWUOA) for optimizing the Brayton power cycles performance, selecting the optimum operating parameters (recompression flow fraction, LTR UA fraction, Pressure Ratio in Compressor, etc).

CSP CONFIGURATIONS

Two CSP arrangements were simulated with Thermoflow [10] in this paper. In Configurations 1, see figure 1 and figure 2, the TIT is up to 400oC. As explained in reference [9] higher TIT requires increasing the SF operating pressure.

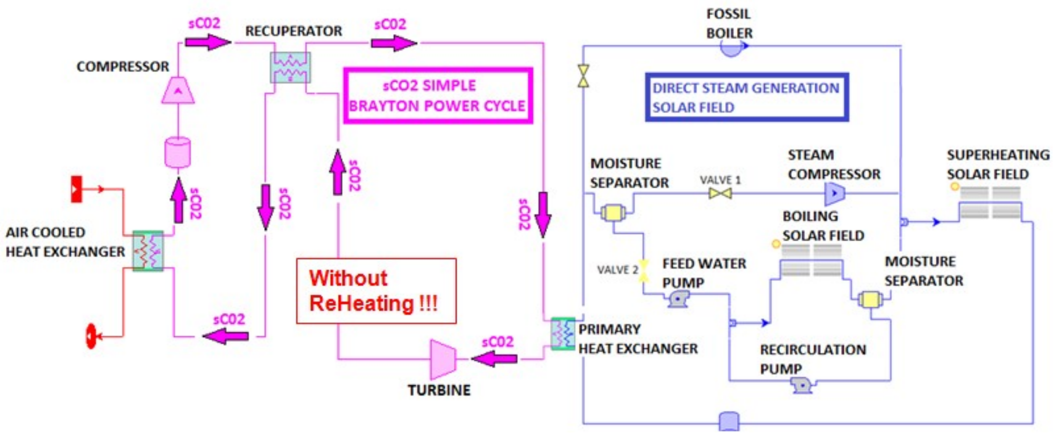

Figure 1. Configurations 1 and 2 integration in the same CSP.

The Configuration 3 suitable for TIT up to 550°C, maximum operating temperatures compatible with the selective material in the receivers.

Both Configurations 1 and 2 could be integrated in the same CSP, as illustrated in figure 1.

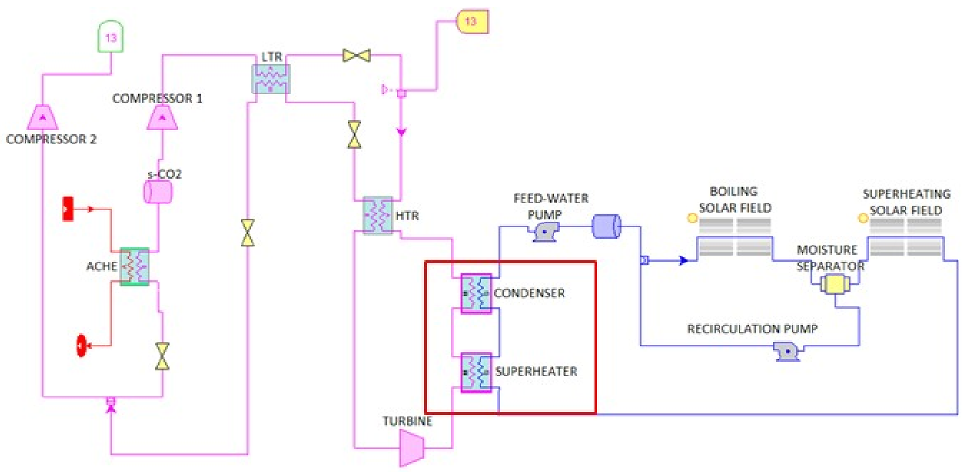

Figure 2. DSG CSP Configuration 1 for TIT up to 550°C.

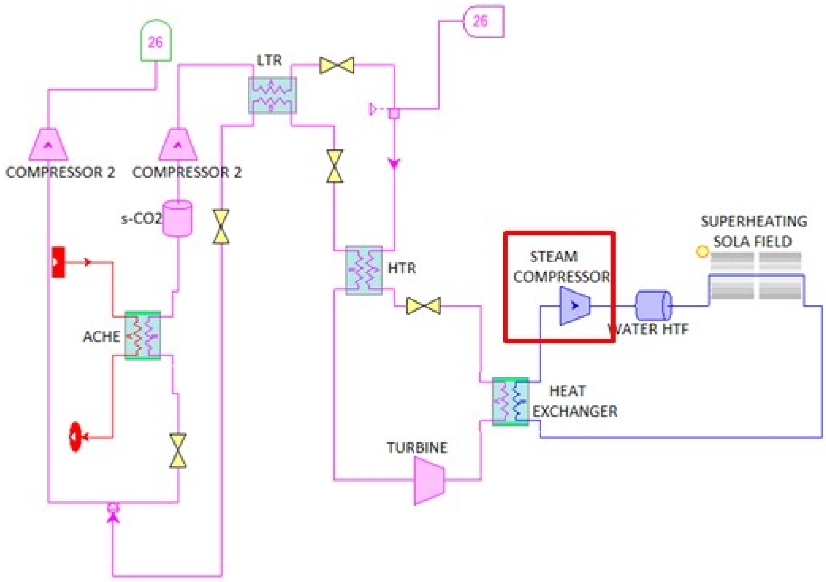

Figure 3. DSG CSP Configuration 2 for TIT up to 550°C.

ASSUMPTIONS

In the Tables 1 to 5 are summarized the main data input considered during the simulations.

Table 1. Location and weather conditions.

Location:	Dagget, CA, USA.
Latitude:	34.86°
Longitude:	-116.8°
Hour zone:	-8
Hour:	11:30 hr
DNI:	986 W/m^2
Ambient Temperature:	25°C
Altitude:	588 m

Table 2. Receiver parameters.

Pipe material:	Stainless Steel
Exterior Diameter:	70 mm
Thickness:	4-8 mm
Internal Roughness:	Ra = 0.0457 mm

Table 3. LF Linear Fresnel solar collector parameters.

Collector type:	SuperNova1 (Novatec)
Dimensions:	16.56 m x 44.8 m
Aperture Area:	513.6 m^2/por module
Nominal optical efficiency:	0.67 (boiling); 0.647 (superheating)
Thermal losses:	$1.06\ \Delta T + 1.2\cdot10^{-8}\ \Delta T^4$ $0.15\ \Delta T + 7.15\cdot10^{-9}\ \Delta T^4$

Table 4. PTC Parabolic solar collector parameters.

Tipo de colector:	EuroTrough II
Anchura de apertura:	5.77 m
Longitud Focal:	1.71 m
Factor de limpieza:	0.96
Eficiencia óptica nominal:	0.75
Pérdidas Térmicas:	$0.141\ \Delta T + 6.4810^{-9}\Delta T^4$

Table 5. Parámetros del ciclo s-CO_2 Brayton.

Turbine Efficiency:	93%
Compressor Efficiency:	89%
Recuperators (LTR, HTR) UA fixed	
No pressure drops in HX	
TIT:	550°C
Turbine Inlet Pressure (TIP):	250 bar
Compressor inlet conditions:	32°C and 74 bar
BOP Auxiliaries energy losses:	0.01% (Gross power)
Generator efficiency:	98.23 (Design-Point)

RESULTS AND FINDINGS

Efficiency and Net power output

In the following Tables 6 to 8 are detailed the energy efficiency and net power output in the CSP configurations studied. When increasing the recuperators conductance UA the net plant efficiency is optimized. But a UA threshold value is stablished around UA=15000 kW/k for all the Brayton configurations. Around this UA value the pinch point in the recuperators are below 2_oC and the net plant efficiency for higher UA continues constant.

Table 6. CSP with a DSG SF coupled to s-CO_2 Brayton RC without ReHeating.

TIT (°C)	**UA** (kW/K)	**SF Config.**	**Gross Efficiency** (%)	**Net Efficiency** (%)	**Net Power** (MWe)	**LTR Pinch Point** (°C)	**HTR Pinch Point** (°C)
400	3000	Configuration 1	33.39	32.34	48434	12.2	17.9
550	3000	Configuration 2	42.94	38.91	45306	24.1	58.7
400	5000	Configuration 1	36.32	35.19	48446	14.8	33.6
550	5000	Configuration 2	46.26	42.16	45572	15.8	30.9
400	10000	Configuration 1	38.84	37.63	48451	8.7	14.2
550	10000	Configuration 2	49.45	45.25	45750	9.1	10.2
400	15000	Configuration 1	39.84	38.61	48457	6.1	7.8
550	15000	Configuration 2	50.54	46.28	45795	4.5	4.5
400	20000	Configuration 1	40.36	39.11	48458	4.6	4.9
550	20000	Configuration 2	51.01	46.75	45830	2.4	2.4

Table 7. CSP with a DSG SF coupled to s-CO_2 Brayton PCRC without ReHeating.

TIT (°C)	UA (kW/K)	SF Config.	Gross Efficiency (%)	Net Efficiency (%)	Net Power (MWe)	LTR Pinch Point (°C)	HTR Pinch Point (°C)
400	3000	Configuration 1	33.94	32.87	48430	20.8	28.4
550	3000	Configuration 2	42.74	38.87	45490	22.3	23.1
400	5000	Configuration 1	35.86	34.73	48438	12.8	13.6
550	5000	Configuration 2	45.15	41.19	45614	9.4	9.5
400	10000	Configuration 1	37.38	36.21	48444	5.1	5.1
550	10000	Configuration 2	46.57	42.57	45727	2.8	2.9
400	15000	Configuration 1	37.83	36.65	48451	2.9	3.1
550	15000	Configuration 2	46.94	42.92	45744	1.6	1.7
400	20000	Configuration 1	38.04	36.85	48450	1.9	2.1
550	20000	Configuration 2	47.085	43.09	45778	1.1	1.2

Table 8. CSP with a DSG SF coupled to s-CO_2 Brayton RCMCI without ReHeating.

TIT (°C)	UA (kW/K)	SF Config.	Gross Efficiency (%)	Net Efficiency (%)	Net Power (MWe)	LTR Pinch Point (°C)	HTR Pinch Point (°C)
400	3000	Configuration 1	34.20	33.13	48443	22.6	0
550	3000	Configuration 2	43.38	39.28	45280	24.3	56.7
400	5000	Configuration 1	36.63	35.49	48457	15.1	32.3
550	5000	Configuration 2	46.68	42.51	45548	16.2	29.5
400	10000	Configuration 1	39.16	37.95	48460	10.1	13.4
550	10000	Configuration 2	49.70	45.46	45737	9.3	9.3
400	15000	Configuration 1	40.17	38.93	48460	6.8	7.3
550	15000	Configuration 2	50.75	46.47	45782	4.1	4.1
400	20000	Configuration 1	40.69	39.43	48460	4.5	4.5
550	20000	Configuration 2	51.21	46.92	45814	2.1	2.1

Solar Field Effective Aperture Area

In the following Figures 4 to 9 are compared the SF areas for the different Brayton cycles configurations and the PTC and LF solar collectors assessed.

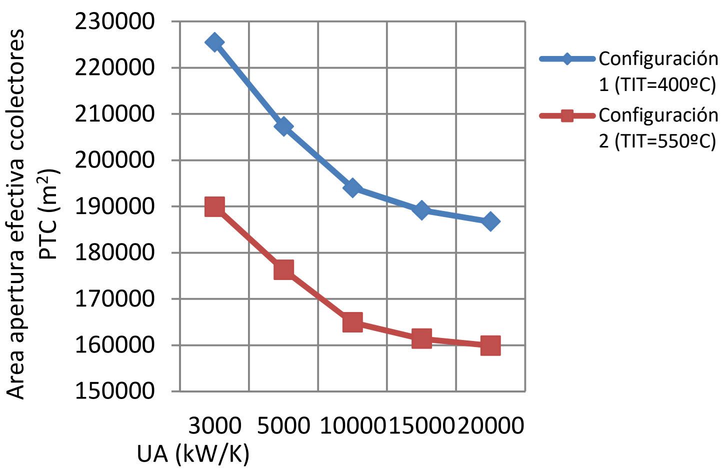

Figura 4. SF apperture area with PTC collectors versus recuperators UA. s-CO_2 Brayton RC without ReHeating.

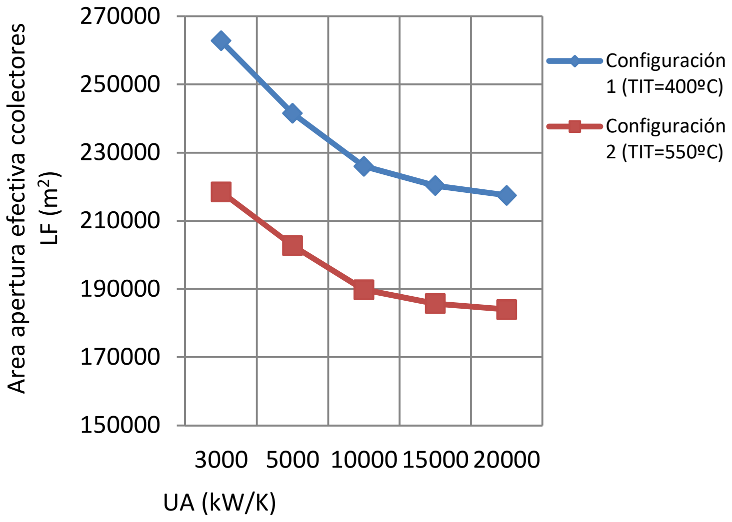

Figura 5. SF apperture area with LF collectors versus recuperators UA. s-CO_2 Brayton RC without ReHeating.

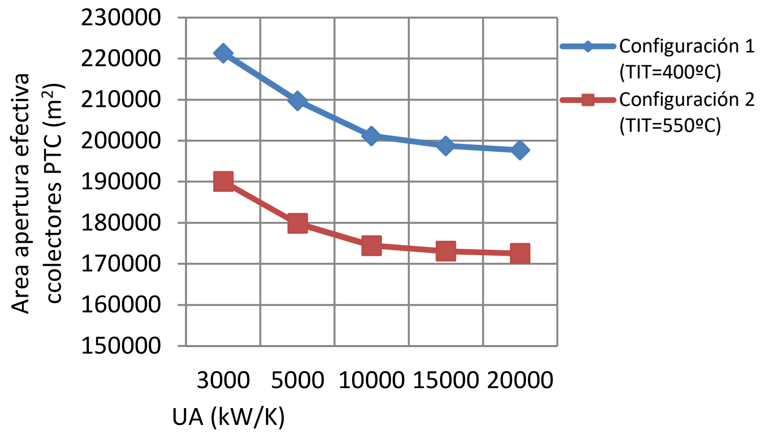

Figura 6. SF apperture area with PTC collectors versus recuperators UA. s-CO_2 Brayton PCRC without ReHeating.

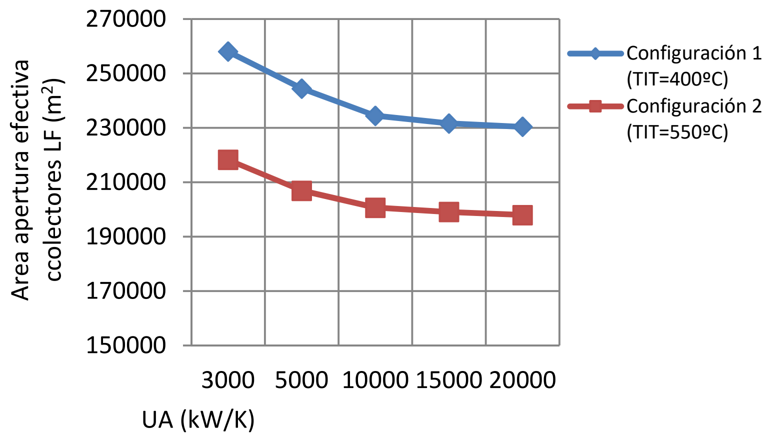

Figura 7. SF apperture area with LF collectors versus recuperators UA. s-CO_2 Brayton PCRC without ReHeating.

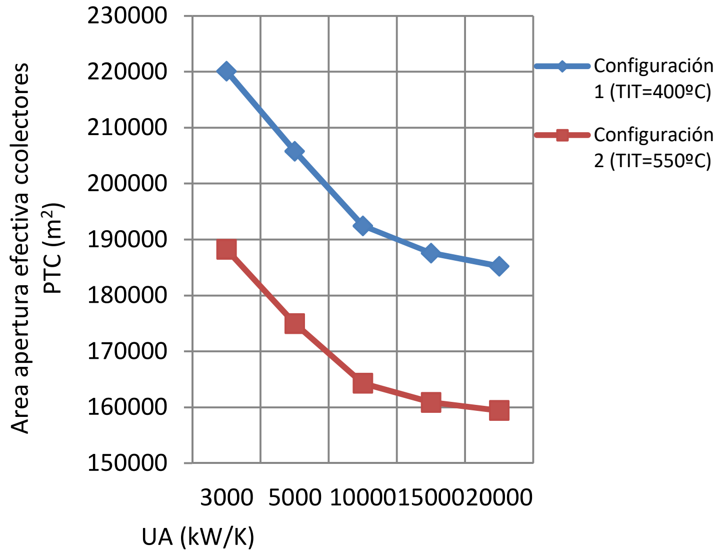

Figura 8. SF apperture area with PTC collectors versus recuperators UA. s-CO_2 Brayton RCMCI without ReHeating.

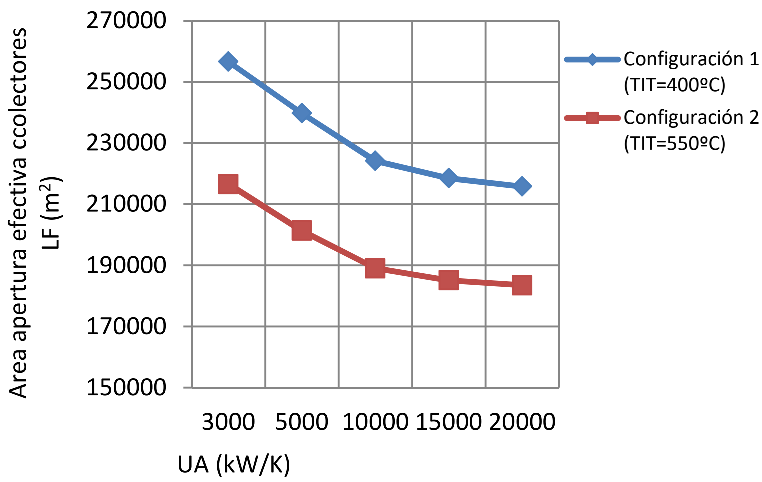

Figura 9. SF apperture area with LF collectors versus recuperators UA. s-CO_2 Brayton RCMCI without ReHeating.

CONCLUSION

The CSP with linear solar collectors (PTC or LF) and a Rankine power cycle is a matured feasible technical solution for renewable power generation. Coupling line-focusing solar plants with Brayton power cycles will provide a new generation of CSP with higher energy efficiency and competitive cost in comparison with the other CSP technologies (central tower, stirling dishes). In this paper are optimized two CSP with DSG configurations coupled to s-CO_2 Brayton power cycles (RC, PCRC and RCMCI). The calculations assumptions in this paper not included the BOP real behaviour: the heat exchangers pressure drops (between 0.5%-1% relative pressure drops), the real turbomachines efficiency (85-90% turbines, and 83-85% compressor), and finally the ambient temperature and Direct Normal Irradiance (DNI) variations. Hence, further analysis are required to compute the final plant energy efficiency. Another important issue to deeply analysis in CSP coupled with Brayton cycles is related with the Ultimate Heat Sink (UHS). In most CSP location is difficult to find water for the UHS, for this reason the “dry” Air Cooled Heat Exchangers (ACHE) are selected as the optimum UHS. The ACHE main drawback is the fans electrical consumption. In this study was considered only 1% Gross power as the BOP auxiliaries energy losses, but in case of adopting the ACHE as UHS, this value should be increase up to 2-3 MWe (4%-5% of Gross power). An important advantage of the DSG+s-CO_2

configurations is related with low material cost in the SF not requiring a high allow steel in receivers. An important handicap is the Brayton cycles equipments, not yet developed for deploying at industrial scale.

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